Advanced Bonding for Large Aircraft

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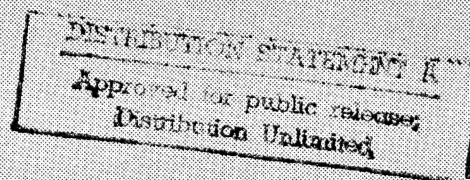
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Prior to birth of the commercial jet age in the late 1950's, few aviation authorities could have envisioned the problems of air traffic congestion that now confront major commercial airports and airways.

A dozen years ago, even the most optimistic market analysts were shy of the mark by several factors when they attempted to forecast air travel growth into the current period. The big, new jetliners introduced onto commercial routes in the late 1950's were envisioned as the ultimate answer to air travel demands, but they have become so numerous in the skies and airports, Figure 1, that yet another forward step in aviation technology is required to meet projected growth during the 1970's and beyond.

In order to assure continued growth at the predicted rate over the next 15 years, it has become essential to find ways to fit more travelers into the existing system of airports and airways. This demand is now being met by the aircraft manufacturing and airline industries with the introduction of a new generation of wide-bodied, advanced technology jet transports.
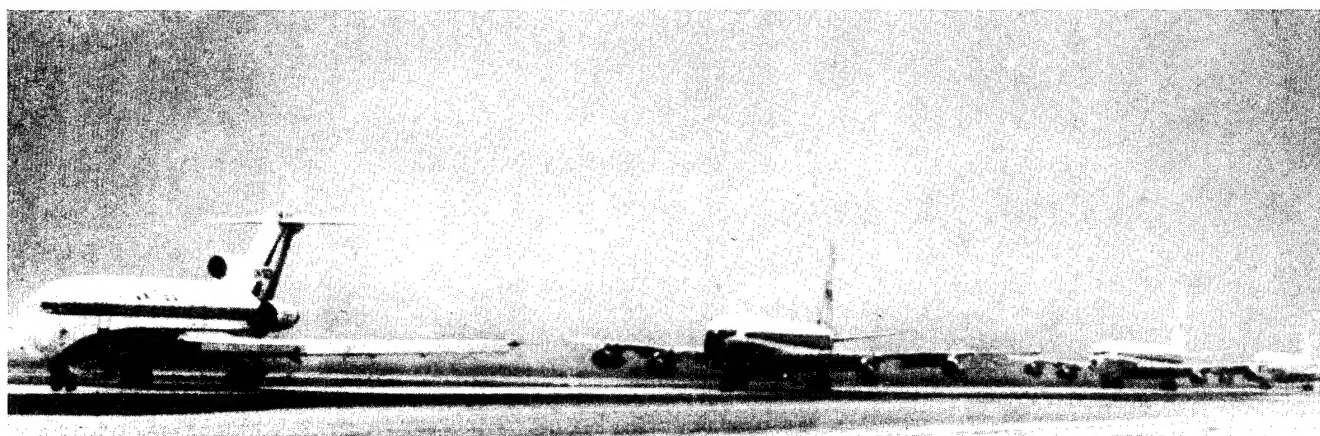

Figure 1.   Traffic Jam

These new aircraft incorporate technical advances in their airframes, avionics and propulsion systems. Design and manufacture of the airframe for this type of vehicle is the subject of this paper.

Aircraft of the new wide-body concept offer not only an ability to carry more than double the loads of previous jets but also a marked improvement in passenger comfort, Figure 2. Both goals have been given high priority by airline managements.

As these new luxury liners are delivered into airline service, it is believed by the industry at large that the theater-like roominess of these aircraft, Figure 3, will produce an expanded market among those travelers already accustomed to flying and also extend the market into a substantial segment of the public that has until now resisted flight as a mode of transport.

The airlines, however, in opening up their inventories to a new generation of aircraft, are assuming no small economic task. The required investment is estimated to be in excess of $25 billion over the next 10 years. Moreover, the initial commitments to purchase these new aircraft are coming at a time when airlines are somewhat painfully digesting the financial aftereffects of a new wave of rising wages, interest rates and other costs.

Plainly, something more than the desire for greater capacity and luxury lay behind the airlines' decision to order the new family of aircraft. It was the promise, offered by the new subsonic giants, of higher profits on operations.
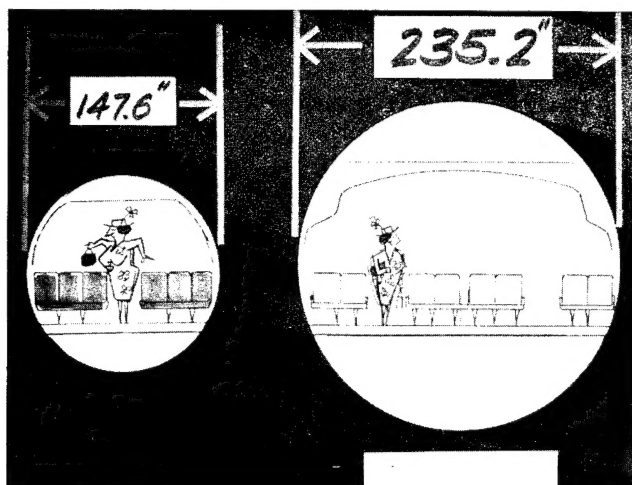

Figure 2.   Comfort Level

Figure 3.   Interior Views

As the concepts gelled, the future operators realized that lower seat-mile costs would be possible as a result of improvements in aerodynamic and propulsive efficiency. But they also realized that one of the surest pathways to higher profits would be through a measurable increase in reliability, effecting the twin results of lower maintenance costs and higher aircraft availability.

With costs of the new jets running from $15 million to more than $20 million each, downtime of these aircraft for maintenance would be more harmful to airline profit sheets than ever before. Daily loss of gross revenue due to downtime could soar into the $80,000 range with these planes.

Thus, the demand was set for engineers of the Lockheed-California Company to design an L-1011 TriStar with an airframe durable enough to

promise essentially unlimited structural life in normal operational service. In effect, profitability become the chief consideration in each step taken in development of the TriStar airplane, from concept through manufacture.

This requirement was more than an ordinary challenge to the Company's design and manufacturing teams. It meant the TriStar body had to be tougher than that of any previous Lockheed plane — yet lighter despite the "square-cube" law. Also, it had to be free from the debilitating effects of corrosion. Every effort would have to be made to inhibit corrosion if the TriStar airplane were, in fact, to have a fuselage with an unlimited life in airline service and if other parts of the aircraft were to provide substantially improved protection against this age-old affliction of aircraft structures, Figure 4. Selection of materials and specified treat-
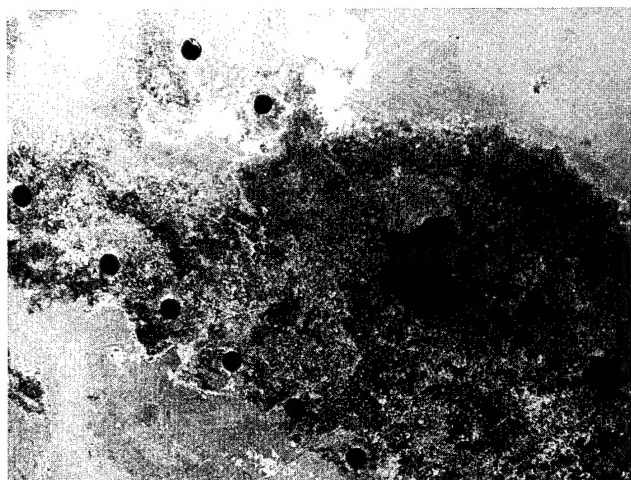
ments were among early steps toward this end, as witnessed by the widespread use of alclad and over-aged aluminum, anodizing of parts, detail parts painting, and the decision to develop paints and primers with fluid resistant (FR) qualities. Similarly, advances in metal bonding techniques resulting in distinct and measurable corrosion resistance led to selection of the metal bonding approach in design and manufacture of the TriStar fuselage.

TESTING

Now, 2-1/2 years after the program was launched, the design effort is complete and the evidence of some thousands of hours of testing bonded structures has been accumulated and analyzed.

The first 12 TriStar aircraft are being assembled, Figure 5, and the first of the new jets is now completed and about to enter a flight test program culminating in type certification and start of deliveries to Lockheed's airline customers.

During the next year, a detailed analysis of the TriStar structure will be conducted during flight, while fatigue and static testing is carried out simultaneously on two ground test TriStar aircraft. Both the fatigue and static test aircraft will be installed in jigs in the flight test hangar at the Company's final assembly and flight test center at Palmdale, California.

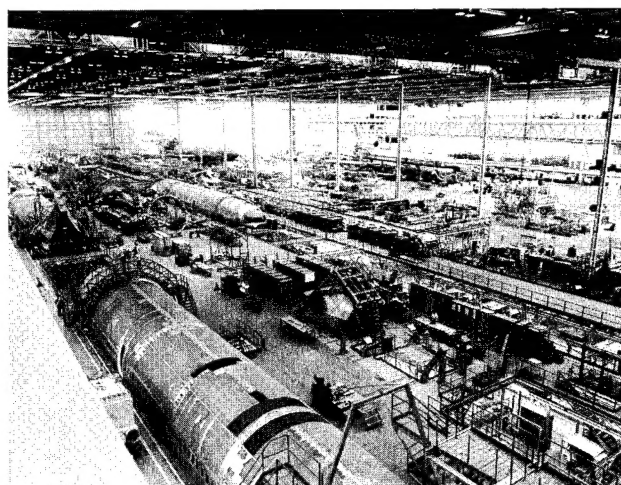Figure 4.   Aircraft Corrosion — Current Aircraft

Figure 5.   Palmdale Assembly

The fatigue test article is expected to have completed cyclic loading equivalent to 20,000 flights by the time the first TriStar is delivered to a customer. This verification of the structure eventually will span 36,000 simulated flights.

Although an important phase of the structural test program still lies ahead, data already have been compiled confirming the essential characteristics sought in development testing of bonded structures. Actual production components, consisting of bonded panels and assemblies, began feeding into the test program more than a year ago.

Foremost among characteristics investigated during the structural tests was fatigue resistance of the bonded joints. Metal bonding does not replace mechanical fastening on the TriStar fuselage, but it has produced for the fuselage a dramatic increase in fatigue resistance over joining systems relying solely on fasteners.

Testing of production panels at Lockheed's Rye Canyon Research Laboratory showed that the TriStar mechanical fastening system alone would achieve sufficient fuselage fatigue strength to meet airline guarantees. But it demonstrated further that adhesive bonding of fuselage panels would add fatigue life to the joints, up to a factor of 10 over the conventionally riveted joints, Figure 6.
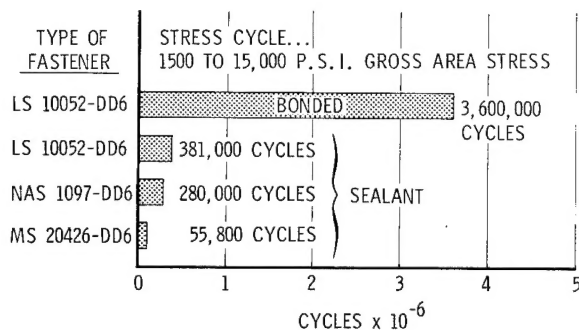
The testing program led to identification of these advantages for the system:

Uniform Load Distribution — Adhesive bonding provides uniform load distribution throughout a joint between a skin panel and the underlying parts, instead of confining loads to the small bearing surfaces around fastener holes.

Resistance to Crack Propagation — Growth of a crack is substantially retarded upon arrival at a bondline, as evidenced by pressurization and cyclic tests at Rye Canyon.

Fail-safe Improvement — Since crack propagation is inhibited throughout a bonded fuselage, the bonded fail-safe titanium straps in the TriStar fuselage provide an additional margin of safety against catastrophic failure. In a typical test of TriStar structures, 8,000 load cycles were required to propagate a crack from the edge to the center of a bonded fail-safe strap, whereas only 3,000 cycles were required for a crack to reach the same point in an otherwise identical structure with riveted straps, Figure 7.

Sonic Fatigue — Bonded structures display an inherent self-damping characteristic in sonic fatigue environments, enhancing resistance to this type of loading.
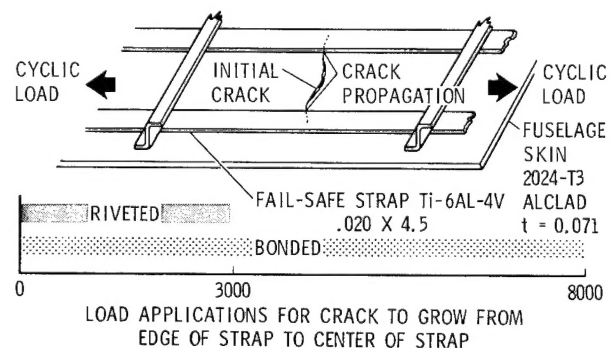
Figure 6.   Constant Amplitude Fatigue Test

Figure 7.   Bonded Compared to Riveted Straps

Careful control of the bonding process and an adhesive with high peel strength and shear strength contributed most to meeting requirements for the TriStar bonding system.

Acoustical Absorption — Bondlines tend to dampen vibration, and tests in acoustical facilities at Rye Canyon demonstrated a measurable difference in sound attenuation between bonded

and riveted assemblies. The adhesive layers absorb certain sound waves, thus reducing noise levels in the aircraft cabin.

Lighter Structures — A reduced net weight is an incidental, but desirable, result of bonding TriStar fuselage panels. Bonding resulted in over a million fewer fasteners, fewer joints, and a distinct weight and cost savings.

Minimum Maintenance — Fuselage repair, being a perennial high-cost factor in airline maintenance shops, was given special attention by TriStar designers. Adhesive bonding contributes to greater fatigue life at the joints and, at the same time, presents a continuous barrier to fluid entry at the bondline, thus preventing and inhibiting corrosion in the multilayer skin areas. Because of these characteristics, maintenance becomes minimal from two major causes of fuselage decay-fatigue and corrosion.

In order to achieve the design and operational characteristics sought for the TriStar fuselage, several major steps had to be taken in close coordination between design and manufacturing engineers. Design goals had to be compatible with producibility.

DESIGN AND PRODUCIBILITY

As developed, the TriStar body is a conventional semimonocoque shell construction with a constant cross-section of 235-inch diameter along most of its length. Bonding is utilized throughout the 150 feet of airframe pressurized zone to join doublers and triplers around openings in the skin, Figure 8. Skin and stringers are supported by sheet metal frames spaced at 20-inch intervals.

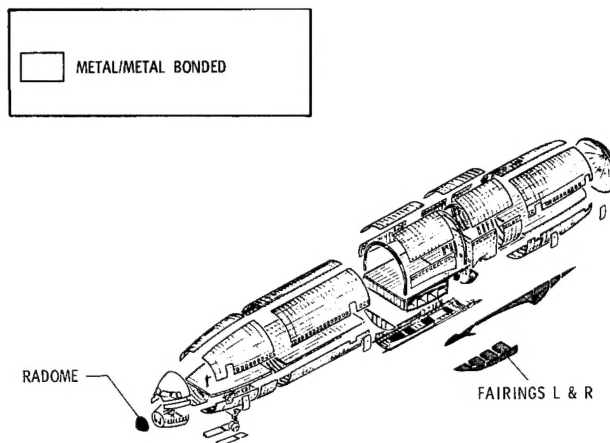☐ METAL/METAL BONDED

RADOME

FAIRINGS L & R

Figure 8.   Structural Bonding — Fuselage

One of the first decisions was selection of materials and the configuration of the respective parts to be bonded. The designers wanted the largest skin panels possible in order to reduce the number of fuselage joints, constituting another step toward broader distribution of structural loads and improved fatigue strength. On the other hand, manufacturing engineers had to ensure that the panels could be produced efficiently, consistent with required quality control.

A cooperative effort resulted in determination that size of the bonded panel assemblies could range up to 38 feet in length and 15 feet in width. Panels of this size are double the dimensions of any previous bonded panels in aircraft resulting in substantially fewer skin joints and an inherent increase in fatigue life. Since fatigue problems arise in joints, fewer joints contribute directly to improved service life for the structure.

An unusual freedom could be exercised in deciding skin panel sizes because the limiting factor—manufacturing equipment—was a flexible issue. This was the case because Lockheed-California Company already had concluded that its existing metal bonding facilities would not be adequate for TriStar production. A major expansion of production capability was approved; and, to a large extent, the new production equipment could then be tailored to meet design requirements, instead of the reverse situation usually encountered.

The new equipment and facilities, by now completed and in full operation, include an all-new metal bonding complex, a new trim and plastic facility, and a large new machine shop at Burbank, Figure 9; and an all-new, more than $50 million final assembly and flight test center at Palmdale, Figure 10, 56 miles by highway north of Burbank.

The pre-production considerations of skin materials led to a choice of 2024-T3 clad for most of the pressure shell and 7075-T76 clad for such
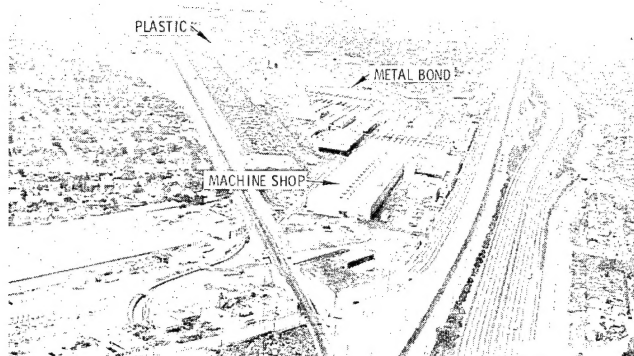

Figure 9.   Burbank Fabrication

Figure 10.   Palmdale Facility

high-stress areas as the over-wing side panels. The considerations were based on the following criteria: fatigue resistance, corrosion resistance, and adaptibility to adhesive bonding.

Next major selection facing the design/manufacturing group was an adhesive with high peel strength, high shear strength, bond line resistant to corrosion, minimum degradation of properties due to adverse environment such as extreme temperatures and corrosive liquids, and not requiring a cure temperature above $260^{\circ}F$.

The requirement for high peel strength in a wide temperature range was set because of the need to carry high shear buckle loads in certain areas where heavy-gage metals are bonded together. Peel strength, determined from climbing drum peel test, Figure 11, was selected as the criteria for determining the ability of an adhesive to carry these loads.
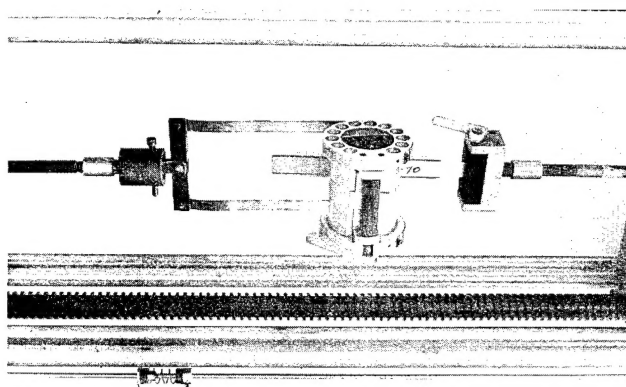

Figure 11.   Climbing Drum Peel Test

Testing of candidate adhesives, however, ran the gamut of destructive and nondestructive analyses, including ultrasonic inspection of bonded samples and lap shear strength separation.

Subsequent testing has established a correlation between climbing drum peel strength of an adhesive and the ability of large bonded panels to withstand shear buckling loads. The correlation was established at $-65^{\circ}F$, because adhesives show their lowest peel strength and the structure would experience its most severe shear buckling loads in this temperature environment.

An upper limit on cure temperature of $260^{\circ}F$ was set because the primary alloy for TriStar skins is 2024-T3 aluminum, which becomes susceptible to intergranular corrosion when exposed to temperatures above that point.

Other criteria applied in selection of an adhesive were:

Uniform Strength Reproducibility — Since bonding would be conducted across broad surfaces, it was necessary for the adhesive to produce uniform properties throughout the bonded area. Gross inconsistencies could result in localized failures that, in turn, could propagate into more firmly bonded areas.

Proven Service of the Adhesive Chemical Class — It was deemed desirable that the chemical class of the TriStar adhesive have a proven record of satisfactory service, despite the fact that it most likely would contain certain unique properties. The development effort conducted between Lockheed and supply firms culminated in the decision that only an epoxy-based material would provide the basic properties capable of meeting the established goals. This chemical class has been in service for more than a decade, during which it has registered excellent performance.

Non-wicking Carrier — Since wicking action on the part of an adhesive film carrier could be a source of fluid entrapment and corrosion, the adhesive must have no carrier, or else one which would not exhibit wicking characteristics. The non-wicking feature is new to the chemical class from which the TriStar adhesive was developed.

Corrosion Inhibiting Primer — As double insurance against even the remote chance of corrosion inside a bondline, it was decided that the adhesive primer must have corrosion resistant qualities. Such a primer would perform further service by providing a fluid resistant seal against corrosive action on non-bonded inside surfaces, since the entire interior surface of a skin panel would be treated with primer. This quality also is new to the selected chemical class.

Repairability in Service — The possibility of future damage to a TriStar fuselage also was taken into account in selection of an adhesive. In the event of such damage, the adhesive must permit drilling for attachment of replacement panels with rivets or fasteners without cracking or crumbling. All bonded areas of the TriStar

were provided with sufficient edge distance to permit field repair service using rivets or fasteners.

After exhaustive testing, selection was made for an epoxy adhesive which met the design objectives outlined. Typical results as compared to existing adhesives are shown for peel tests in Figure 12, shear strength in Figure 13, corrosion resistance in Figure 14, and stress corrosion in Figure 15.
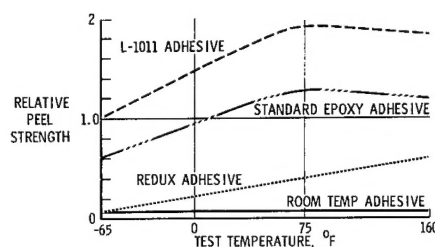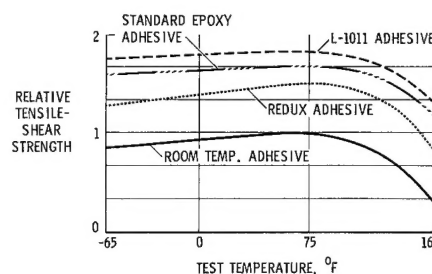

Figure 12.   Peel Strength
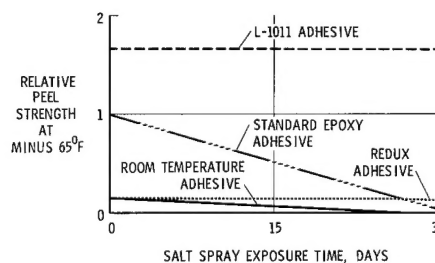

Figure 13.   Shear Strength
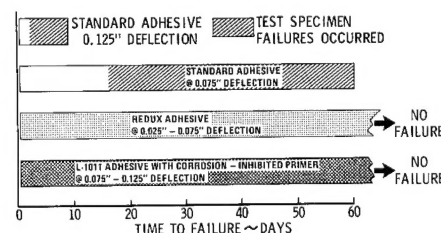

Figure 14.   Corrosion Resistance

Figure 15.   Stress Corrosion

Although the preceding tests and analyses established an adhesive with properties required for design purposes, its suitability for manufacture of TriStar skin panels at the required speed and simplicity was still unproven.

Testing for this purpose centered on the following manufacturing variables: primer thickness, bondline thickness, heat-up rate during cure cycle, exposure of the part of multiple cure cycles, life of the adhesive film at shop temperatures and ability of the adhesive system and associated processes to preclude air entrapment.

Coupon tests were followed by tests of larger panels, which were dissected afterward and from which coupons were cut at various locations for shear and peel testing. Other areas of the panels were chem-milled away to expose large areas of the bondline for visual examination. Results indicated that bondline strength on the panels was superior to that obtained in lab tests on the original test coupons. They also indicated the desired absence of porosity.

These tests concluded early evaluations of materials and basic processes. Tests of full-scale TriStar panels would resume after design and installation of the large new production equipment required for the manufacturing program.

With major design requirements of the TriStar bonding system identified, planners in the Manufacturing Operations Branch then addressed themselves to specification of the production equipment and the operating limits that would be required for process control.

MANUFACTURING AND PROCESS CONTROL

The metal bonding complex at Burbank is encompassed within a 400- by 600-foot area largely inside a previously existing building. It consists chiefly of 8 major processing points, connected by 5-1/2 miles of automated overhead conveyor system.

Because the TriStar panels are twice the size of those in any other aircraft, the metal bonding equipment includes several units that are unique in size and/or design concept. The two equipment units that shape the panels, a forming roll and a stretch press, are the largest of their respective types in existence. The autoclave, 22 feet in diameter and 66 feet long, is the largest "pressure cooker" ever built.

Weight of the skins, ranging up to 387 pounds, required that handling equipment be mechanized and in many cases automated. Vacuum lifting cranes handle the skins in most places where they are being removed or replaced on the conveyor system.

Skins enter the bonding complex at a receiving point where they are inspected and then sprayed with an elastomeric protective coating, Figure 16. This point also marks the start of the conveyor system. The panels, with a fresh protective coating on the outside surface, are suspended from load
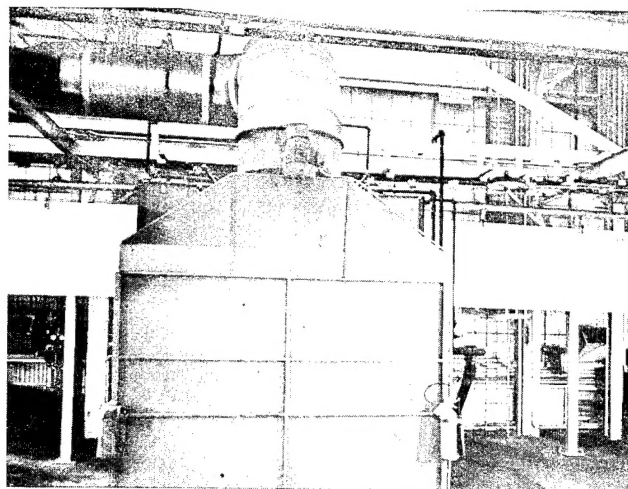

Figure 16. Elastomeric Protective Coating

bars on the conveyor system, Figure 17, and dispatched toward the first major processing point, either the forming roll or stretch press. Enroute they pass through an enclosed section lined with heat lamps that cure the protective coat.

INCOMING SKINS

5½ MILES
OF CONVEYOR
SYSTEM

PROTECTIVE COATING
FORMING
UNPROCESSED STORAGE
PREFIT
CLEANING LINE
PRIMER
CLEAN STORAGE
TAPE ROOM

AUTOCLAVE

Figure 17.   Conveyor System

Lockheed's new stretch press, Figure 18, is capable of exerting pressures up to 1 million pounds in shaping TriStar skin panels requiring compound curves, such as those in the forward and aft body closures. The press, built by Cyril Bath, is a hydro-mechanical unit with capacity to handle 8- by 40-foot panels.

Tolerance to which the stretch press must work depends on the individual skins. Some panels may be formed with deviation not exceeding + .015 inch, while tolerance permitted on others may
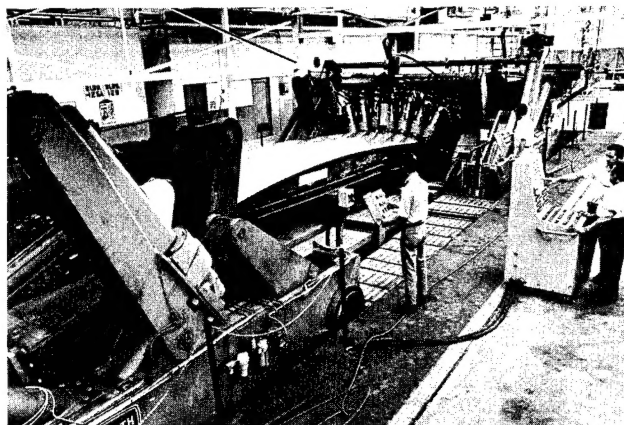
Figure 18.   Stretch Press

range up to + .032 inch. Factors governing tolerance are gage thickness of the skins, location on the fuselage and the degree of bonding required on the panel. If the skin is to receive substantial bonding, it generally requires the smaller tolerance figure.

The roll, Figure 19, built by the Farnham Division of Lisk-Savory Corporation, is the largest
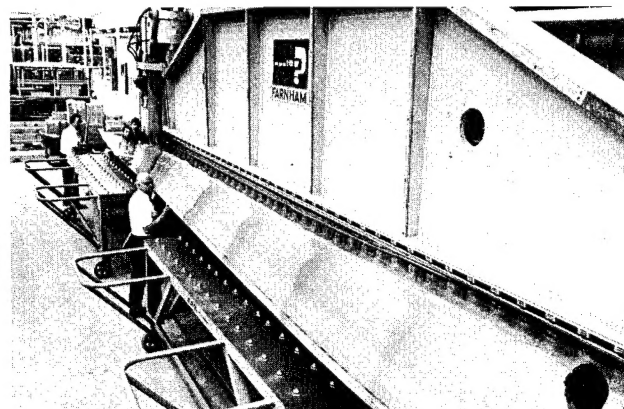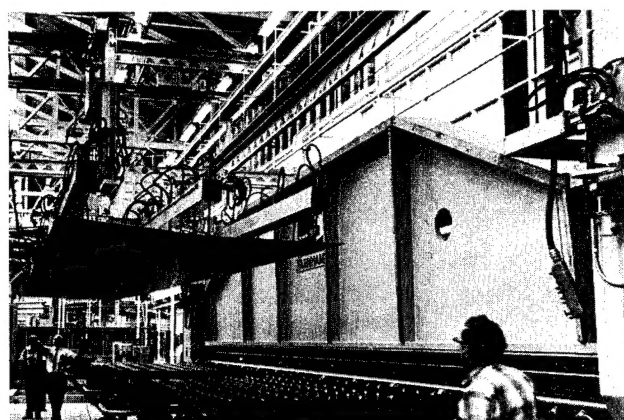

Figure 19.   Farnham Roll

precision roll of its type ever built. This roll is capable of accepting skins up to 38 feet in length. Owing to its long bed length, the machine presented some design problems for the manufacturer. The three individual rolls, in pyramid configuration, are so long that, without some means of support, they would sag several thousandths of an inch in the center. Support of the two bottom rolls presented no great difficulty, but this was not the case with the top roll. The problem was solved by development of a series of overhead permanent magnets, Figure 20, that uplled the roll upward into firm contact with a set of precisely placed bronze bearings.
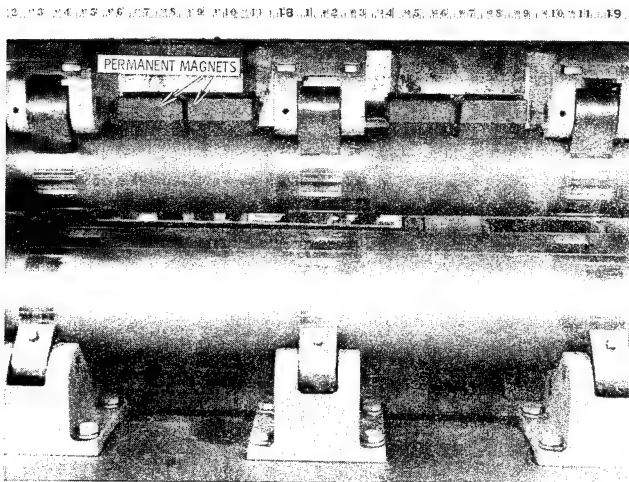
Figure 20.   Upper Roll Magnetic Support

The machine bends panels for the constant curve segments of the fuselage under pressure exerted by hydraulic cylinders at either end, each developing up to 300,000 pounds of force.

The protective coating on the skins is not affected by forming in either of these machines or by any other process in the metal bond complex.

From the roll or press, the skins are sent via conveyor either to a storage area, Figure 21, to the pre-fit line. At the latter site, Figure 22, the panels are installed in metal bond fixtures for pre-fit of their doublers, triplers, fail-safe straps, etc., to ensure that there is no need for further trim or metal-work beyond that point.
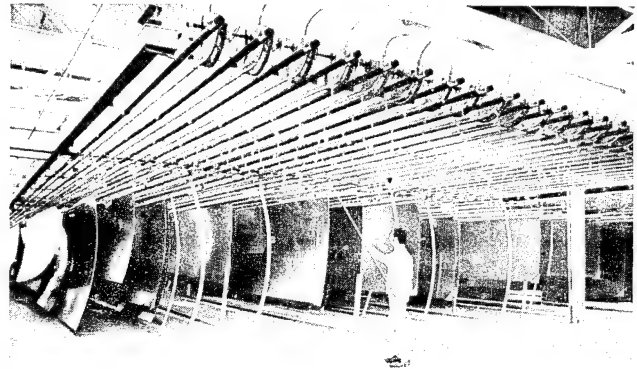

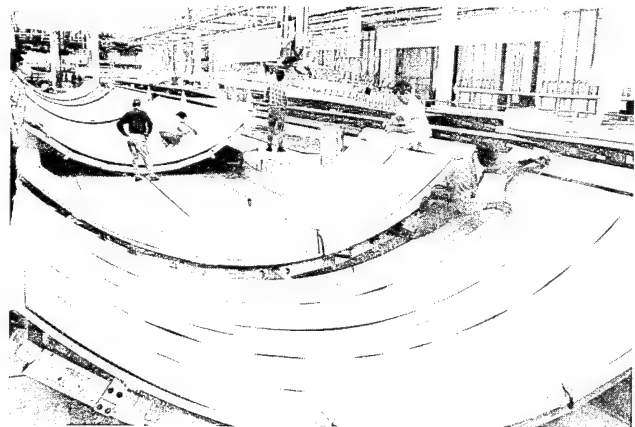Figure 21.   Skin Storage Area

Figure 22.   Prefit Line

All panels, whether requiring pre-fit or not, pass next through an automated car-wash type cleaning line, Figure 23, that was designed, built and installed by the Purex Corporation.
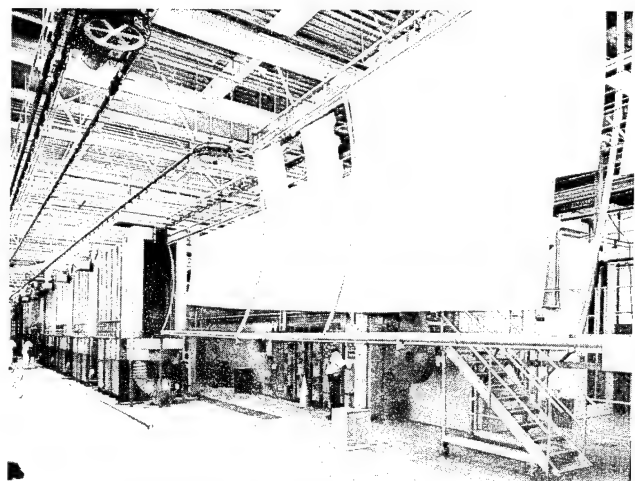

Figure 23.   Clean Line

This phase in the metal bonding process is one of the most critical, for even the smallest particle of foreign matter will cause a void in the bondline. For this reason, the cleaning operation is continuously monitored to ensure proper concentration of chemicals in the various solutions.

Prior to entering the series of booths in the cleaning line, larger panels are simply suspended from their customary load bar on the conveyor, while smaller and lighter doublers and straps are mounted from springs inside a "picture-frame" fixture.

Traveling at about 5 feet per minute, the parts require 28 minutes to travel the 142-foot-long cleaning line.

The first step in the cleaning process is to wash the panels with an alkaline solution heated to 160°F. The panels then pass through an air knife and into a tap water rinse, followed by another alkaline spray bath at the same temperature and pressure as the first.

Another air knife treatment and tap water rinse precede a more thorough rinsing with hot demineralized water.

The metal surfaces have remained unaffected up to this point, but the next step, a wash with sulphuric dichromate acid at 160°F imposes a distinct etch to the inside surface of the panels. Purpose of this treatment, obviously, is to provide a surface that lends itself to maximum adhesion during bonding.

Another demineralized rinse, followed by passage through a hot-air dry booth, completes the cleaning procedure. Between the two final steps, a technician minutely inspects the panels for water breaks, which would indicate retention of particulate matter or other impurities. If such a water break occurs, the panel is sent through the line again.

The panels emerge from cleaning into a temperature and humidity controlled room, ready for the next process.

The next step is application of the adhesive primer which, like all the other primary processes, requires rigid controls in order to assure proper characteristics in the bondlines.

The epoxy-based primer is applied through a De Vilbis system, Figure 24, with a conventional spray, using air filtered of all oil and moisture. The path followed by the moving spray head is calculated to project a full and uniform coating. Both qualities are necessary to provide consistent mechanical properties to the bondline, as well as future corrosion protection in service.
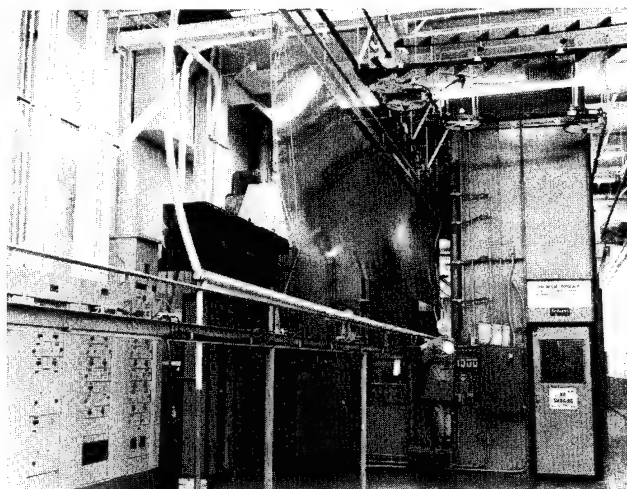

Figure 24. Adhesive Primer Line

After priming, the panels rest in a holding area for 45 minutes, while flash-off of volatile solvent takes place, and then they go into the 250°F curing oven for 60 minutes.

Primed panels from this point go directly into a humidity and temperature controlled "clean" room for storage. This room is located above the lay-up room, where the adhesives are applied to the panels and sub-components laid up prior to bonding.

When a particular panel is "called" out of storage, it is lowered through a doorway in the

ceiling of the lay-up room, Figure 25, still suspended from its load bar. Its associated doublers, triplers and straps, also still attached inside picture frames, descend with it.
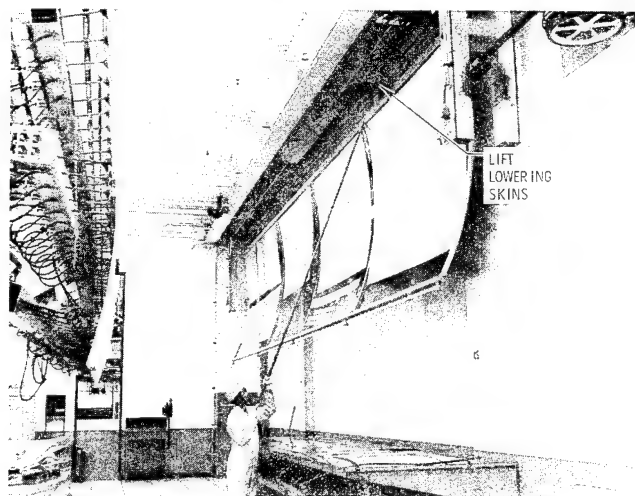

Figure 25.   Skin Lowered From Storage

The features incorporated into design of the 50-by 250-foot lay-up room, Figure 26, and the procedures followed guarantee freedom of contamination for the panels during the lay-up process. The air is filtered and humidity and temperature controlled. A slight overpressure is maintained in the room, and the only permanent opening is protected with an air knife. Large roll-up doors are located at either end of the room, but air knives also protect these openings from the time a door is opened until it closes.
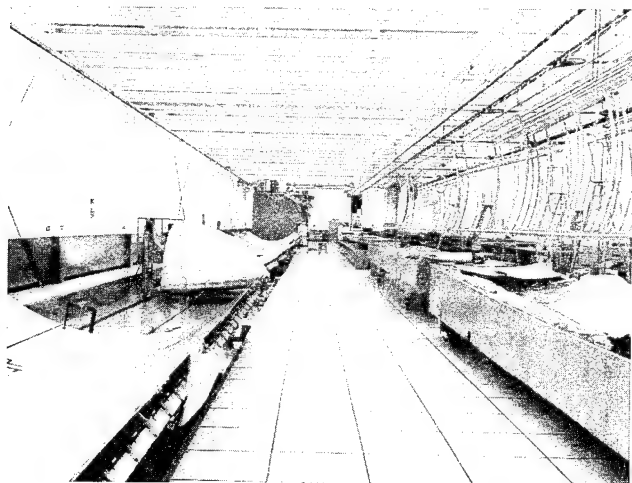
Figure 26.   Lay Up Clean Room

Personnel working in the room wear white caps, smocks, gloves and "wing" socks. Finally, a particle count is maintained of the atmosphere, and the room is wet-scrubbed every other day.

Lay-up, Figure 27, is performed in a conventional manner, with the skin installed on a trim table. The adhesive, like its primer, is a modified epoxy. It is about 12 to 15 percent solids, with a solvent base and a dacron carrier to prevent deformation during handling. The dacron also helps control adhesive flow-out during the pressure and cure cycle in the autoclave.

The adhesive is 0.010 inch thick at time of lay-up, flowing out to between 0.004 and 0.007 inch thick during cure.
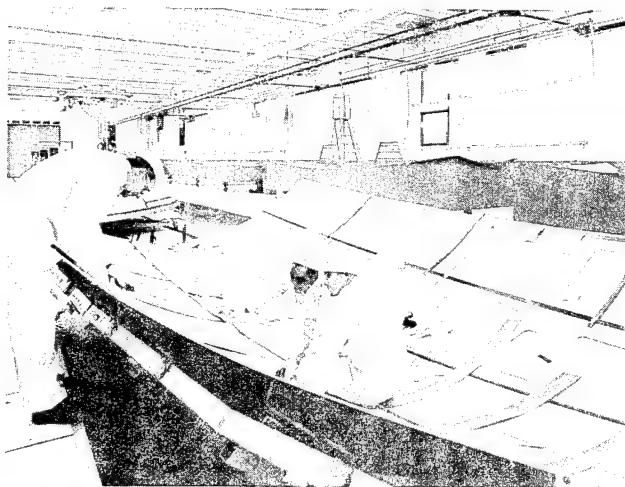

Figure 27.   Lay Up

Some panels require "sandwiched" areas with up to five layers of metal. Nylon tape, applied to the sandwich areas after lay-up ensures against displacement of installed doublers and other supporting members prior to bonding.

With lay-up complete, the panels are transferred to metal bond fixtures (MBF's) where they are shrouded and sealed inside plastic bags. Vacuum is introduced inside the bag equal to about 10 psi creating downward pressure on the parts. The

MBF's are loaded aboard a large wheeled transporter, Figure 28, via an elevator just outside the lay-up room, and then dispatched on a 150-foot trip to the waiting autoclave.
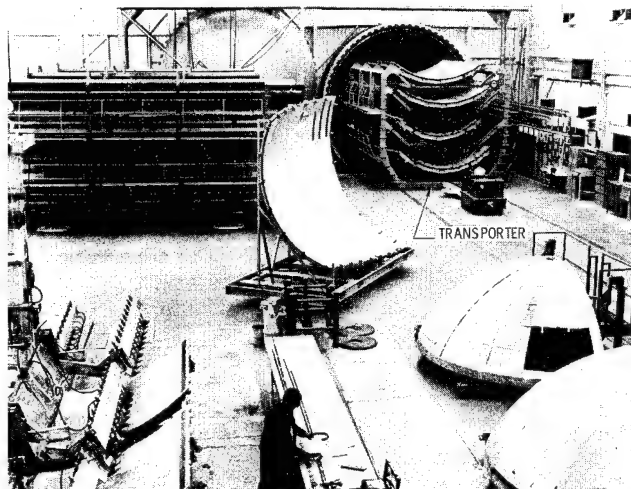

Figure 28. Metal Bond Fixture Transporter

During the autoclave phase, carefully defined process controls again play the primary role in ultimate success of the bonding operation. The autoclave, Figure 29 and 30, although the largest in
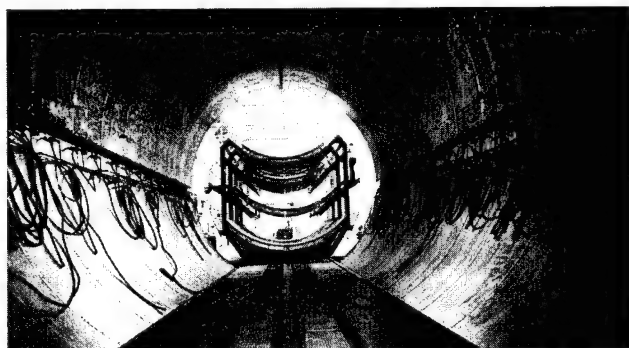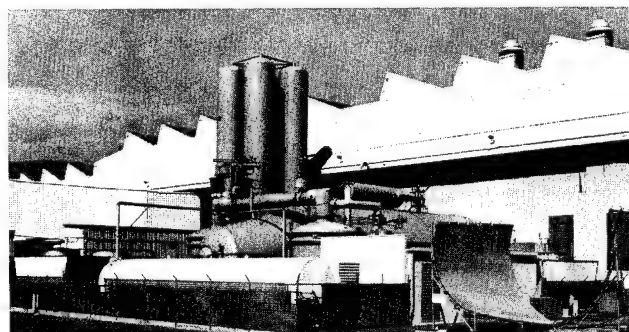

Figure 29. Autoclave (Interior View)

Figure 30. Autoclave (Exterior View)

existence, also is one of the most sophisticated in terms of precision controls and redundancy of systems.

Its physical components are a 300-ton pressure cylinder, with a wall thickness of 1-7/8 inches, and a 25-ton door operated by its own overhead crane. Four accumulator tanks, each as tall as a five-story building, Figure 31, store inert gas produced by a generator fired with natural gas. The large physical size was selected to provide capacity for full rate production of the L-1011.
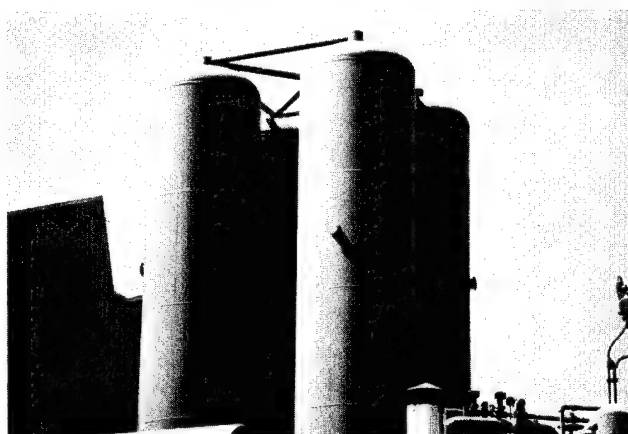

Figure 31. Inert Gas Storage Tanks

Stored liquid carbon dioxide provides an alternate source of inert gas for pressurization. Heat source is one of two alumina oxide pebble beds, also heated with natural gas. Only one pebble bed is used to heat the autoclave, with the other in standby readiness during bonding operations.

Control systems generally offer up to third level of redundancy for all steps in operation of the facility, while interlocks and sensors provide security for personnel, equipment and the production components.

Although the autoclave has the capability to operate at 600°F and 150 psi, bonding for the TriStar requires only 250°F temperature on the part at a pressure of 135 psi.

A full cycle from closing to opening of the autoclave door usually requires about 3-1/2 hours.

Steps preceding start of the cycle include attaching vacuum hoses to each of the plastic bags enclosing individual panel assemblies and attachment of thermocouples, usually 12, to each MBF.

The cycle begins with inert gas valved into the sealed autoclave to a pressure of 110 to 115 psi. As pressure passes the 30 psi mark, vacuum to the plastic bags is shut down and the hoses vented to the atmosphere.

At the intermediate pressure level, a check is made of the plastic bags. Even the most remote leak can be detected. Integrity of the bag must be maintained throughout, as any perforation would result in an unsatisfactory bond and rejection of the panel. To date, no such rejection has occurred.

At this point, temperature is introduced into the autoclave, and both temperature and pressures begin a rise, with temperature held for 15-minute dwells at 160° and 190^OF. After pressure reaches its maximum of 135 psi, temperature starts on a graduated scale to the cure level of 250^OF.

Both temperature and pressure are held at the cure level for one hour, followed by a one-hour cool-down and removal of the bonded assemblies from the autoclave.

Immediately upon removal, the assemblies are stripped of the plastic bag and otherwise cleaned and prepared for inspection.

First step in inspection is test of the peel and lap shear coupons, Figure 32. Up to now, ultrasonic inspection for voids has been performed manually with a portable tester, but an automated system is now installed and undergoing pre-service checkout and calibration.

When it enters production status in November 1970, the automated system will have the capability of rapidly scanning in a longitudinal direction, vertically indexing in discrete increments. A panel assembly having an adhesive bonded area 38 feet long by 80-inch chord will be inspected in a maximum of 3 hours, with the possibility of reducing inspection time to 1 hour on panels with a relatively constant section.

Scanning will be performed by 20 transducers — 10 transmit and 10 receive — mounted on an 8- by 8-foot bridge riding on 50-foot-long tracks, Figure 33. The panels will be positioned over the mobile bridge.

A single UM 721 ultrasonic scope will pulse, receive and gate information, with a 10-channel multiplexing unit providing sequential signal from the transducers to the scope.
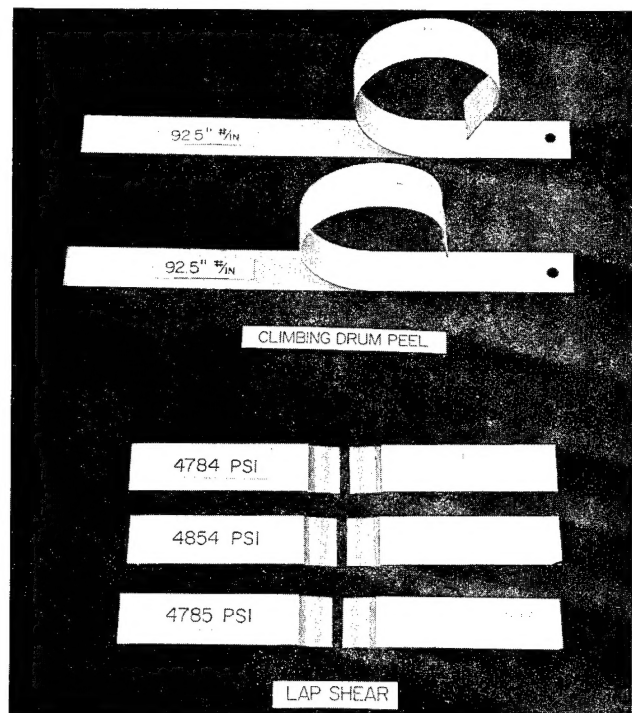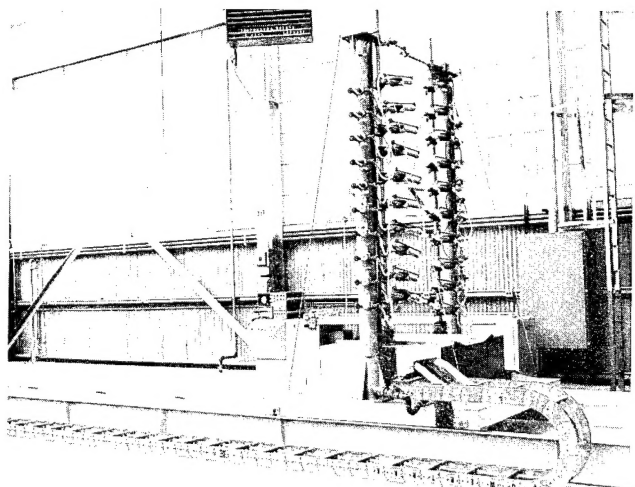

Figure 32. Test Coupons

Figure 33. Automated Ultrasonic Tester

A 10-channel dry paper chart recording will serve as a go, no-go permanent inspection record, and any flaw in the bondline will be presented as a break in the lines 0.010 inch in length or greater, depending on the flaw size.

Manual techniques will be utilized to dimensionally locate and evaluate the flaw. Manual ultrasonic inspection also will be used in bonded areas outside the 80-inch chord section, or within the 80-inch chord section where more than two bondlines exist.

Manual inspection will be conducted from a powered platform, also mounted on 50-foot tracks, and operated under control of the technician.

Inspection precedes the last major process step in production of TriStar bonded skin panels, painting, prior to delivery of the panels for assembly operations.

The painting sequence constitutes another major provision for elimination of corrosion in the TriStar. Bondline edges are first shot with a 6-inch-wide coating of epoxy-based fluid resistant (FR) primer, followed by another coating over the entire interior side of the panel assembly.

For most of the panels above the passenger floor, this is sufficient. But with panels destined for the aircraft's bilge area and selected zones of panels above the floor, the process continues with two additional layers of white polyurethane top coat.

In between the polyurethane coats, an epoxy-based sealant is applied to bondline edges as further insurance against fluid entrapment. Those areas above the floor receiving bondline sealant and polyurethane treatment include broad zones around door cutouts and any surface that remains in contact with insulation blankets. Insulation is mounted on stand-offs below the floor.

The combination of painting and sealing processes enumerated above, along with use of an FR adhesive and FR adhesive primer for bonding, virtually precludes fluid invasion of the bonded joint during the life of the aircraft in normal airline service.

The bonding system equipment is now installed at Burbank, having entered production status in August, 1969. Imperfections in the bondline were uncovered in some panels produced during preliminary qualification testing of the equipment. But the adjustments required in process control to eliminate the cause of the imperfections were correctly identified, and since start of routine production approximately 420 panels of all shapes and sizes, Figures 34, 35, and 36, have been successfully bonded without a single rejection, despite intensive ultrasonic inspection and careful analysis of each production panel's test coupons.
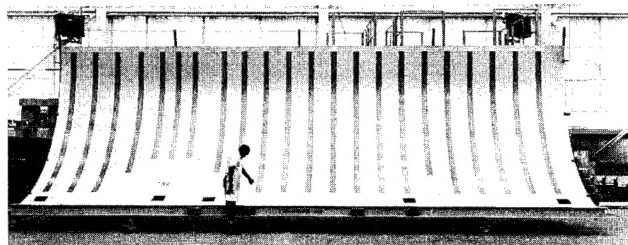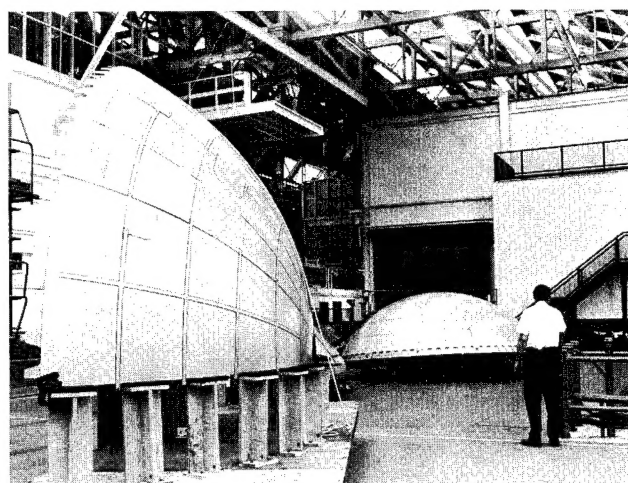

Figure 34.   Large Panels
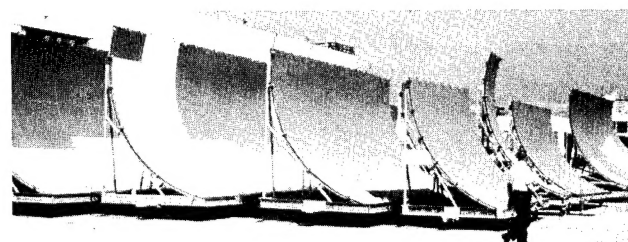

Figure 35.   Aft Pressure Dome

Figure 36.   Panels Prior to Subassembly

The panels are made up into quarter-section subassemblies, Figure 37, also at Burbank and then transferred to Palmdale. At the new Palmdale facility, the panels are assembled into half sections, Figure 38, and then into full barrel segments, Figure 39, followed by mating of the segments into the completed pressure vessel, Figure 40.
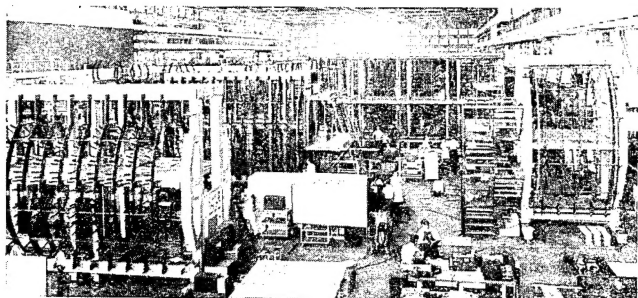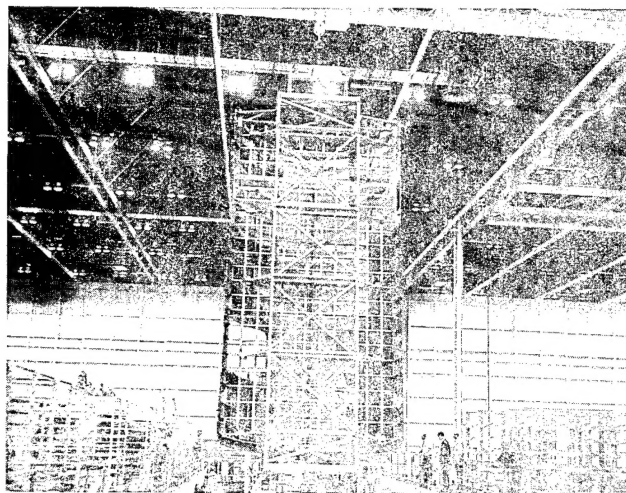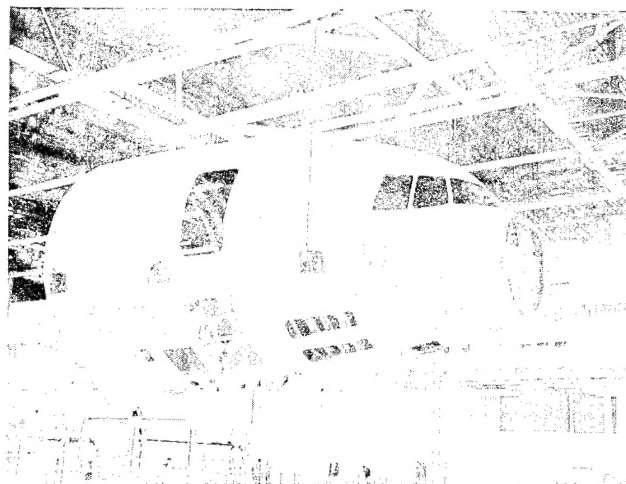

Figure 38.   Half Section

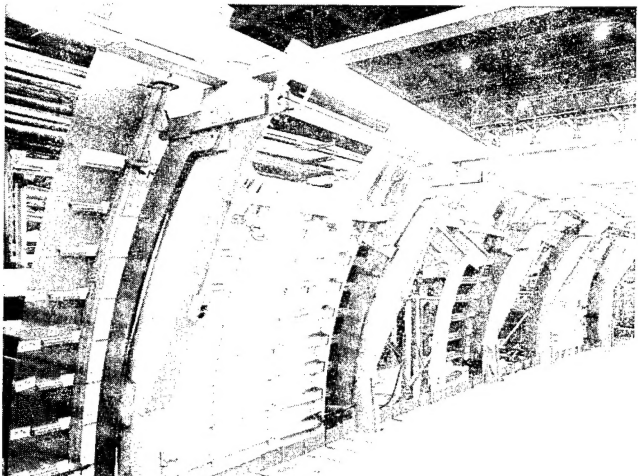Figure 37.   Subassembly (Quarter-Section)
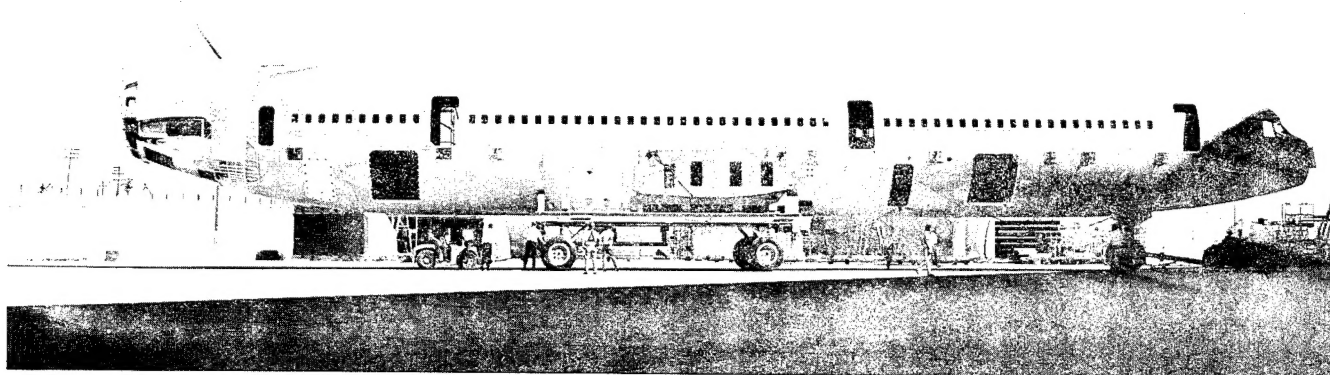

Figure 39.   Fuselage Barrel

Figure 40.   L-1011 (Pressure Vessel)

Completion and rollout of the first TriStar jet on schedule, Figure 41, September 1, 1970, marked the culmination of 2-1/2 years of concerted effort on the part of design, test, manufacturing and facilities engineering groups at the Lockheed-California Company to produce an aircraft incorporating advanced adhesive metal bonding. The result is an aircraft with unparalleled strength, corrosion resistance and serviceability.

Figure 41.   L-1011 Rollout

SUMMARY

Adhesive bonding of aircraft skin panels, as developed for the L-1011 TriStar, has established a number of improvements that were unattainable in purely riveted structures.

The carefully controlled and detailed tests that accompanied this development have verified repeatedly the results sought by Lockheed's design and manufacturing teams. Reliability of the fuselage and resistance to fatigue and corrosion were uppermost among the desired goals, and these have been proven conclusively through conventional and more recently developed test techniques.

Further testing is expected to develop additional information, derived primarly from flight and simulated flight programs. Data from both flight testing and the fatigue and static test vehicles will be compared with predicted values and the results of previous component testing.

Ultimate findings are expected to advance the state-of-the-art in airframe manufacture and establish a new level of reliability and profit potential for commercial aircraft.

ACKNOWLEDGEMENT